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THESIS

DISCRETE EVENT SIMULATION MODEL OF THE POLARIS 2.1 GAMMA RAY IMAGING RADIATION DETECTION DEVICE

by

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June 2016

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This thesis was performed at the MOVES Institute

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The nuclear threat remains a top priority for the United States government; there are many agencies whose sole focus is thwarting terrorist actions. As layer upon layer of both passive and active defensive measures are employed, the research community continues to bear new tools to aid in detection of radiological material. Incorporating and developing tactics, techniques, and procedures (TTPs) for those devices becomes a challenge in and of itself. For this thesis, the Polaris 2.1 Gamma Ray Imaging Radiation Detection Device (Polaris) was selected as the technology to be modeled. The platform, Simkit, was utilized to create a discrete event simulation (DES) model of the Polaris. After carefully constructing the DES, multiple simulations were run measuring the time to detect all radiation sources in the simulated environment. Then, all data and parameters from the simulation were used for statistical analysis to determine significant factors in the DES—for example, not only was the strength of the radiation source significant, but so was the amount of variance introduced into the DES. These results are non-intuitive and pave a path for further research to enhance the DES and find the optimal TTPs for this device from both the tactical and operational perspectives.

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DISCRETE EVENT SIMULATION MODEL OF THE POLARIS 2.1 GAMMA RAY IMAGING RADIATION DETECTION DEVICE

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ABSTRACT

The nuclear threat remains a top priority for the United States government; there are many agencies whose sole focus is thwarting terrorist actions. As layer upon layer of both passive and active defensive measures are employed, the research community continues to bear new tools to aid in detection of radiological material. Incorporating and developing tactics, techniques, and procedures (TTPs) for those devices becomes a challenge in and of itself. For this thesis, the Polaris 2.1 Gamma Ray Imaging Radiation Detection Device (Polaris) was selected as the technology to be modeled. The platform, Simkit, was utilized to create a discrete event simulation (DES) model of the Polaris. After carefully constructing the DES, multiple simulations were run measuring the time to detect all radiation sources in the simulated environment. Then, all data and parameters from the simulation were used for statistical analysis to determine significant factors in the DES—for example, not only was the strength of the radiation source significant, but so was the amount of variance introduced into the DES. These results are non-intuitive and pave a path for further research to enhance the DES and find the optimal TTPs for this device from both the tactical and operational perspectives.

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THESIS DISCLAIMER

The reader is cautioned that the computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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LIST OF ACRONYMS AND ABBREVIATIONS

CBRN	Chemical Biological Radiological Nuclear
DHS	Department of Homeland Security
DES	Discrete Event Simulation
DNWS	Defense Nuclear Weapons School
DTRA	Defense Threat Reduction Agency
EMP	Electromagnetic Pulse
FREAK	Force-on-Force Evaluation and Analysis of Key Performance Parameters
GeGI3	Germanium Gamma-ray Imager
GNDA	Global Nuclear Detection Architecture
GPS	Global Positioning System
GUI	Graphical User Interface
I/ITSEC	Interservice/Industry Training, Simulation and Education Conference
IND	Improvised Nuclear Device
JMP	JMP Pro 12
LLNL	Lawrence Livermore National Laboratory
MOVERS	Mobile Vehicle Based Emergency Radiation Monitoring System
POLARIS	Polaris 2.1 Gamma Ray Imaging Radiation Detection Device
RDD	Radiological Dispersal Device
SuperMISTI	Super Mobile Imaging and Spectroscopic Threat Identification System
TTP	Tactics, Techniques, and Procedures

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I. INTRODUCTION

A. THE THREAT

Billions of dollars are spent on national security from research and development to manning guard stations across the United States. There are areas that have received more attention than others such as airports due to the attacks on 9/11. However, the United States must remain vigilant and cognizant of alternative methods in which terrorists might seek to harm and disrupt the American way of life. With thousands of miles of coast line to protect, there are countless points of entry into the United States; however, the majority of the goods that enter the United States are channeled through seaports along the two coasts. With a large cargo container capable of moving thousands of tons of goods and products, there lies a vulnerability that has long been a challenge for the United States. The Department of Homeland Security (DHS) must ensure that those items inside the containers coming through the ports are in fact as indicated on the manifest and do not contain nuclear weapons or radiological dispersal devices (RDD). DHS screens thousands of containers each day in search for that needle in a haystack scenario by utilizing advanced technology, brilliant minds, and watchful eyes to spearhead this DHS mission. DHS does not work this mission alone, nor is it confined to the United States

The Department of Homeland Security (DHS) supports the Global Nuclear Detection Architecture (GNDA) in an effort to expand the detection of illicit radioactive material no matter the location (DHS, 2015). Whether the material is underwater, in the sky, or hidden in a cargo vessel, the GNDA is a “multi-layered defensive network to detect and assist interdiction of radiological and nuclear materials out of regulatory control,” and is the current solution to the threat (DHS, 2015). In order to make this a valid and successful mission, there must be tools, training, and systems in place throughout the globe. There is no single solution to accomplish this mission. Therefore, a multi-partnered team of technologies, scientists, analysts, and law enforcement are tasked with this challenge.

Traffickers and would-be terrorists remain unyielding, seeking to obtain illicit radioactive materials. Schmid and Spencer-Smith (2012) noted over 300 different instances of radioactive material being purchased, stolen, found, or removed between 1990 and 2011 in the eastern European and Middle East areas. While some incidents appear to be less than nefarious in nature, the majority are apt depictions of deception, greed, and potential terrorism (Schmid & Spencer-Smith, 2012). Many of the excerpts occur during the fall of the Soviet Union, but 15 years later the area still remains a hotbed for black marketing of radioactive material. From uranium fuel rods stolen by security guards to illicit sales of plutonium on the black market, it is a scary thought indeed to see what traffickers do for profit (Schmid & Spencer-Smith, 2012). While these data are from 2012, there is substantial evidence that the black market has continued trafficking radioactive materials. For this reason the GNDA is not limited to the United States. In order to take this fight to the enemy, a global effort has been engaged to make it more difficult for sellers and buyers of radioactive materials. Also of note is the fact that many seizures occur during border crossings or at airports. Conversely many seizures are also accomplished by underground sting operations (Schmid & Spencer-Smith, 2012). A network of detection portals, undercover agents, and nations willing to stop these crimes are all necessary to make an impact.

Coincidently, not every occurrence of a stolen radiation source was for the purpose of harming the public or spreading fear. In 1985 a radioactive source of Cesium 137 was removed from an abandoned hospital in Goiânia and broken apart at a junkyard with the intent of making some extra cash (International Atomic Energy Agency, 1988, p. 1). This incident led to 112,000 personnel screened for radiation, 249 of which were contaminated, resulting in twenty casualties, and four deaths (International Atomic Energy Agency, 1988, p. 2). Although this story is tragic and spawned a great deal of radiophobia and discrimination against the people of Goiânia, there were no traces of malicious intent with the radioactive material which is why DHS needs to remain hypervigilant to all cases of radiation detection (International Atomic Energy Agency, 1988, p. 115).

B. THE POLARIS

One system that is currently on the market and introducing a new capability to the radiation detection world is the Polaris Gamma Ray Imaging Device (Polaris). The Polaris is unlike many of the other radiation detection devices in that it provides a real image for the operator to see where the radiation source is located. This small suitcase-sized device contains two cameras on either end that captures an image and can overlay the radiation field for any isotope loaded into its library with that image. The Polaris provides isotope identification, radiation activity levels, spectrograph, and wireless capability allowing the user to generate a report and send off to a reach-back entity for further analysis on the isotope in question. In Figure 1, one of two cameras is visible in the center of the Polaris with a number of cables and adapters are part of the suite. At roughly 30 lbs., the Polaris can be operated in the field with an internal battery running and a spare ready to go, or it can be hooked up for direct current to recharge and run experiments. For experiment or real world scenarios, the tablet or laptop used to interface with the Polaris will display any previously recorded data. Both images and spectrograph can be viewed on the tablet or sent over the internet to another unit if need be.

Figure 1. Polaris 2.1 gamma ray imaging device

The Polaris 2.1 gamma ray imaging device detects, identifies, and locates radiation in a given area. With the Polaris are cables, battery, and a tablet to be used by the operator. Source: H3D et al. (2015, p. 6).

This new system may seem like a small player in the big scheme of national security but its added capability can have a significant impact in radiation detection. Before widespread deployment of the Polaris, it is important to identify its potential impact. An effective way of doing so is to create a simulation model of the Polaris and its specification.

C. DISCRETE EVENT SIMULATION

In this thesis, a Discrete Event Simulation (DES) was of the Polaris sensor was developed with the intent of seeking the operational fit of the Polaris. This is not the first time technology got ahead of tactics techniques and procedures. In WWII, American naval power focused on battleships and later transitioned to aircraft carriers after discovering aircraft carriers as the force multiplier. The Department of Defense has a relatively new capability at its disposal, portable gamma ray imaging, and it is yet to be determined how this capability fits into the operational picture. The purpose of this thesis is to create a DES that captures the essence of the Polaris, so that future work can launch forward with seeing where it makes the most sense to place that capability.

A challenge in building a discrete event simulation (DES) model for this project is in deciding what parameters and fidelity need to be incorporated to mimic the Polaris 2.1. The intent of this model is to develop a useful tool that can be further developed or manipulated with more realistic capabilities and limitations of the Polaris as software upgrades are introduced. Therefore another goal of this DES model is flexibility and the dimensionality to allow follow on work or to offer developers another tool to analyze operational use.

There are a myriad of different factors a computer modeler could attempt to replicate when focusing on the Polaris sensor. From Figure 1, a modeler would not be able to deduce which factors are most beneficial to the system. A modeler could focus on the image detection and strictly hone in on measuring the resolution of the image displayed and the response time of the operator. Conversely, a modeler could strive to model the dynamic environments a Polaris may be used in and how those environments effect the time to detect a radiation source. This thesis will focus on the time to detect a stationary radiation.

The specific data to input as capabilities and limitations for this equipment are classified. Therefore generic values were utilized as placeholders. This allows the Defense Threat Reduction Agency (DTRA) or H3D to input actual values into the DES to see for example, the added benefit of extended battery life on a degraded system. The DES model is built to represent the Polaris 2.1 and requires a number of parameters in order to capture and analyze the response variable. Distance to source, shielding, source type, ambient temperature, and background radiation levels are a few. Some of the parameters will be simple variables with just two possible selections, while others will have multiple options to choose from. The reason for developing a DES model to conduct the simulation is due to the high number of factors to be analyzed. Running experiments with different parameters may be of importance but in order to identify those with the most significance and with a large number of trials, a DES is a good way to target those factors. In addition, working with DTRA and applying data from their recent experiments provides realistic approximated data for the DES model.

It is important to note that the Polaris' capabilities are increasing and being enhanced. The DES model in this thesis only considered its current capabilities. As of July 2015, a new GPS tracker and source location has been added to a top down bird's eye view map. When used alongside an additional Polaris this new feature can help triangulate the location of a radiological source and potentially reduce the time required for location. In previous versions the overlay of the hotspot on the real time picture did not decipher whether the source was coming from a wall or the room behind the wall, and therefore led to confusion. This may be of operational significance when a trigger is set off on a radiation detection device aboard a vehicle; the operators can stop the vehicle, run the Polaris and determine the location of the source in both area and depth (M. Black, personal communication, September 22, 2015). Some new features will allow building schematics to be uploaded and used for enhanced situational awareness prior to entering an area. Instead of going room to room, the operators can focus directly on the hotspot. The DES was developed using Polaris' current capabilities.

It is estimated that finer pixelization will enhance operator's ability to identify the shape of the radiation source (M. Black, personal communication, September 22, 2015). With further development, standoff may be increased as well as distinguishing between radiological dispersal devices (RDD), radiological exposure devices (RED), improvised nuclear devices (IND) and nuclear weapons. As software enhancements continue, it remains to be tested how much more capable the operators of the device will be. However, pixelization will not be added to this discrete event simulation (DES) although the image shape may give orientation of the discovered radiation source to the operator. The orientation may assist during rehearsals or in a test environment and help teams know what to expect before dispersing to search for a radiation source. A DES could be built that takes into account the shape of the isotope and add a stochastic variable to annotate the difference in operator's capabilities to recognize the shape and report it as the radiation source in question. There are many opportunities for building a DES on different aspects of the Polaris sensor and yet the Polaris is just one of many sensors on the market for detecting radiation.

II. LITERATURE REVIEW

A. NUCLEAR DETERRENT

Neuhauser (2015) depicts the contrast of nuclear weapons, nuclear stockpiles, and their effectiveness as a deterrent. He brings to light the opposing scholastic approaches that speculate as to whether the possession of such weapons does in fact deter nations from going to war, or whether they are given too much credit. Neuhauser (2015) points to the arguments made for nuclear weapons and the correlation, if not causation of nuclear weapons being the reason for there not having been a global scale war. However, one could counter that nations might as well arm every country with nuclear weapons, to prevent any war and thereby result in world peace (Neuhauser, 2015). This counter argument is in jest but does challenge the nuclear weapons deterrent theory.

When Neuhauser (2015) mentions the U.S. having thousands of nuclear weapons, he points out China, Pakistan, and India as having a minimalist point of view with regards to nuclear weapons. For those in favor of this approach, he does counter that reducing the nuclear stockpile is much more difficult than a normal reduction in numbers. The ties associated with nuclear weapons go well beyond the economic impacts of a few states. From congressmen to general officers to national laboratories, they each have vested interests in the sustainment of nuclear weapons (Neuhauser, 2015). However, Neuhauser (2015) does present the counter argument that, if nuclear weapons are kept at the current numbers; there is a high associated cost that directs right back into previous arguments of reducing or ridding the military of nuclear weapons.

Yet if a terrorist organization is set on developing an IND or purchasing a nuclear weapon from the black market, then deterrence is not enough and securing borders becomes even more paramount. Meissner (2010) addresses some of the challenges of science and technology in designing and implementing a detection device that is effective, low cost, and somewhat portable. More importantly than just the conceptual device to solve radiation detection at ports, she highlights the importance of effectively screening the billions of tons of cargo that flow through seaports along the United States coastline every year.

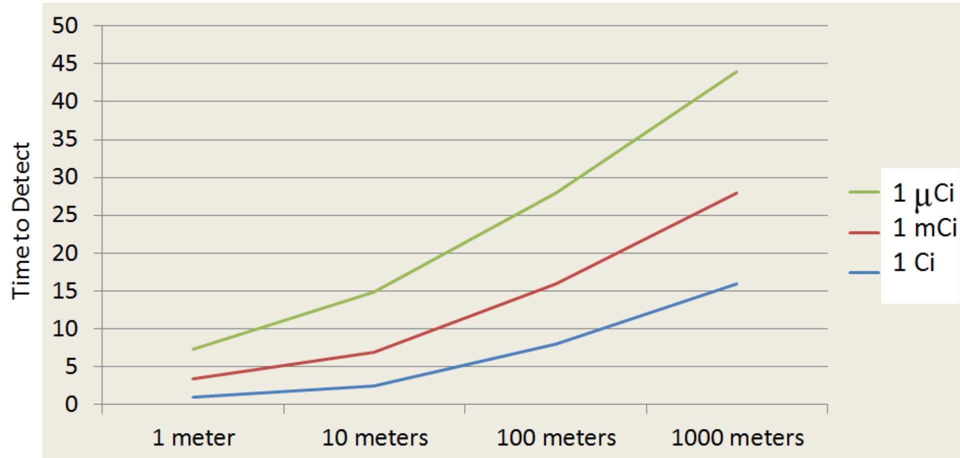
B. ON-THE-HORIZON RADIATION TECHNOLOGY

There are a number of radiation detection technologies in development, on the horizon, and being fielded that make radiation detection a relevant topic. This section will cover the Polaris 2.1 and seven other technologies used for radiation detection and or training operators tasked with handling radiation equipment as well as some of the pros and cons with regards to the Polaris.

In 2015 students, faculty, and operators conducted experiments with Lawrence Livermore National Laboratory and the Defense Threat Reduction Agency's Polaris 2.1 Gamma Ray Imaging device. One of the primary objectives of the experiment was to become familiar with the Polaris as a radiation detection system and to provide recommendations on future use (Bordetsky et al., 2015, p. 11). After conducting multiple experiments with mixed results, the team concluded from the moving vehicle experiment that slower speeds, below 15 miles per hour, were best for detecting radioactive sources (Bordetsky et al., 2015, p. 14).

Of all the other technologies doing radiation detection, the most interesting note regarding Polaris is the lack of modeling. The Polaris uses a deterministic model to calculate detection with a great degree of accuracy, but that only covers how the equipment works, not how to implement it (M. Black, personal communication, March 30, 2016). With the Polaris being a substantially different type of radiation detector, not completely stationary and not as mobile as hand held devices, a discrete event simulation (DES) is a way to bridge the gap with the ultimate goal of identifying best practices for implementation. Figure 2 shows a semi-linear pattern of detection, where the longer the Polaris stays in a specific location, the greater the detection range with detections times depending on the strength of the radiation source.

Figure 2. Fictitious sample of Polaris deterministic model



Adapted from DTRA's deterministic model is fictitious representation of the Polaris 2.1 detecting a lightly shielded radiation source.

However, detecting radiation in a changing environment for the purpose of developing better techniques tactics and procedures for this device requires a new and stochastic approach. Before discussing the DES in further detail, there are a number of radiation technologies to discuss such as the research being conducted at the University of California-Berkley and Lawrence Livermore National Laboratory.

At University of California-Berkley and Lawrence Livermore National Laboratory, the technology Meissner (2010) presents would shoot photons and measure via scintillators the amount of gamma rays bouncing off fissile material that passes through the cargo (Meissner, 2010, p.18). In lay terms, it scans the cargo for radioactive material with minimum radiation hazard. Meissner (2010) does acknowledge the fact that the cost of reducing the speed at which cargo can pass through these ports of entry remains high as delays to this multi-billion dollar industry are not a viable option and are therefore a constraint to security measures. The alternative for security would be to lock down all ports and scrutinize each cargo container as it arrived, essentially putting traffic to a halt. With the massive amounts of cargo to screen, it literally turns finding a shielded or hidden source into a needle in a haystack scenario. Meissner (2010) still interprets the operational scenario of any new technologies added for screening as falling in line with the extensive chain that cargo goes through from check point to check point. She does mention the need for the detection device to identify the source of radiation as well as the relative size which is of relevance as not all detectors identify the source of radiation but rather its presence.

One of the aspects of the experimental equipment mentioned by Meissner (2010) that is in line with the Polaris sensor is the low acceptable alpha error. More specifically, Meissner did mention that their system would need to detect a source as little as under a kilogram in weight. This is pertinent as the Polaris currently gives activity and location; however it does not provide size estimation. However, current software upgrades are scheduled to enhance the pixel quality for a better representation of the shape of the radioactive material (M. Black, personal communication, September 22, 2015).

Although the enhancements in cargo screening would occur with the system proposed by Lawrence Livermore National Laboratory (LLNL), Meissner (2010) does not mention any detailed specifics of the system itself. Acknowledging that the article is dated 2010, she does not mention any kind of network capabilities or visual image of the cargo as it is screened. This leaves the question, how much of the screening process will be left to the observer sitting in front of a monitor and left for interpretation versus how much will be automated such as trigger radiation levels? Additionally, Meissner (2010) does not mention any kind of calculated delays or necessarily slow speeds that cargo would need to travel when being scanned by their device.

There are other technologies that are currently being researched to detect radioactive material being smuggled into the United States. Gamma ray imaging detects radioactive material and it is more sensitive to those materials with higher activity such as Cesium 137 or Cobalt 60. However, another technology under development is Muon Scatter Topography (MST) (Thomay et al., 2012, p. 3). More specifically, MST searches for materials that the gamma-ray imaging devices are not exactly designed for, special nuclear material (Thomay et al., 2012, p. 13). The MST scans for highly dense materials without emitting any radiation. Thomay (2012) conducted tests on the same 20 foot container used to ship goods across the oceans which is ideal for the needle in the haystack scenario (Thomay et al., 2012, p. 10). Even with the results, there were some "problematic" scenarios identified, and some factors that stated even with this "cheap" technology in place, there are still methods to defeat the radiation detection technology (Thomay et al., 2012, p. 13). However, this technology in conjunction with other smaller devices as depicted in Figure 3 may be important to identify what characteristics in a radiation detection device are most beneficial at a seaport or in an airport. Further research is warranted in identifying these factors in relation to this device.

Figure 3. RGU-100 high sensitivity military pocket radiac

The radiac device displayed is a Canberra product that detects radiation in a given area. A device of this size and design makes it easy for users to navigate as well as operate. Source: “RGU-100” (n.d.).

The Naval Research Laboratory developed a gamma ray imaging device capable of maritime operations called the Super Mobile Imaging and Spectroscopic Threat Identification system (SuperMISTI). The SuperMISTI comprises multiple systems that include a high-purity germanium detector and a sodium iodide detector. There are several key factors that make SuperMISTI an attractive piece of equipment. The detection standoff, 3D plot, and ability to operate it while afloat make it extremely valuable. In comparison, the Polaris 2.1 sensor is better suited for a steady and immobile surface while attempting to detect radioactive material. The SuperMISTI, as seen in Figure 4, can detect material while aboard a ship moving at 25 knots, further exploiting its mobile capabilities. The SuperMISTI fits inside two 20 foot ISO containers with a 49,000 lb. approximate weight and boasts detection of radioactive material over 100 meters away (Hutcheson et al., 2012, p. 361). In addition, GPS has been added to the system to aid in localizing and pinpointing the source of radiation.

Figure 4. SuperMISTI aboard a ship

The SuperMISTI detects radiation and gives the user an image overlaid a real image of the direction it is sensing. This figure displays the SuperMISTI inside the two large white rectangular containers with two water tanks alongside that act as a counter balance for the motion of the water. Source: Hutcheson et al. (2012, p. 362).

The features of the SuperMISTI make it very capable but less portable than Polaris 2.1. The SuperMISTI does not fit inside of a suit case; however its detection, identification, graphical user interface and wireless capability are relatively comparable. A semi-truck carrying MISTI technology may be capable of parking outside a building to try to locate and identify a source, while the Polaris can be walked inside the building, taken to the 20th floor and set outside the elevator to begin scanning a room for potentially harmful radioactive material. In the same scenario the SuperMISTI would be stuck at the base of the building trying to get a reading of a source.

Noting that the Department of Homeland Security's Domestic Nuclear Detection Office is heavily invested in this system, it would be interesting to compare sea state effects on detection capability for maritime interdiction operations. Just as aircraft are limited by weather conditions, would the Polaris sensor equally be limited by sea state conditions? Would it hamper the image and GPS quality or just the picture captured? Currently the Polaris needs to be relatively motionless while capturing data. It can take measurements aboard a ship; however excessive motion will quickly distort its image quality.

Another mobile detection device already on the market and civilian made is the Mobile Vehicle based Emergency Radiation Monitoring System (MOVERS) developed by Canberra. MOVERS is similar to SuperMISTI in that it is a system of systems that integrate to give the user a complete picture. Comprised of multiple detection devices with an option to upgrade, MOVERS seems like the ultimate radiation response vehicle as visualized in Figure 5. GPS and wireless capable, MOVERS can track and monitor bringing additional situational awareness to the operator, Chemical Biological Radiological Nuclear (CBRN) cell, and Incident Commander. Canberra is well known in the radiation detection world. The suite of highly sensitive and real time data collection from MOVERS makes it a potentially valuable for team patrolling and protecting a high-value asset. As advertised it is rather conspicuous. However, with a news vehicle logo on its side could blend into a crowded street without drawing excessive attention to the wires and cables sticking above the roof.

Figure 5. MOVERS radiation detection and mapping

Mobile Vehicle based Emergency Radiation Monitoring System (MOVERS), located inside the van, detects radiation and tracks the location of those measurements on software provided to the user. Source: “Movers,” (n.d.).

Unfortunately, specifics on its actual capabilities are limited. The Canberra website’s factsheet does list detection levels, but nothing on the effects of a moving vehicle. If it can detect while moving, how slow must it be going? The ADM606M portable multifunction ratemeter that comes standard with MOVERS gives dose and dose rate alarms, but does it provide direction or location? No details are mentioned in this category, and since this device is mounted inside the van, it is limited to van access. Also, without any visual image of where the source is coming from with the exception of a map overlay, nothing in MOVERS displays a real image of what the operator is seeing when peering out the van window. The MOVERS display does show hot and cold areas of radioactivity while driving around however when putting boots on the ground a different device will be needed to locate the source. For a post-event contaminated area this may be a great tool to have ready to go in order to grab a quick assessment of the levels of contamination and compare them with hazard prediction models to give Incident Commanders the most accurate picture of what areas are indeed safe.

From the 2015 Interservice/Industry Training, Simulation and Education Conference (I/ITSEC), there were hundreds of ideas on how to simulate and improve training and Argon Electronics focused specifically on CBRN aspects. At first glance, it appears to be a “God’s Eye View” of a city map with an interactive window that allows the user to add different CBRN events to a scenario (“Products,” n.d.). However, what makes the system much more unique than just another plume modeling software is that the user can control via a remote where the user is on the city map. This adds a real-time effect that allows the user to maneuver through the city in a natural sweeping pattern or in response to an intelligence report and when the user gets near that area, an actual device that a field user would have in hand begins to alarm (“Plume SIM,” n.d.). Argon Electronics offers a multitude of devices for each type of CBRN for simple detection, to identification, to incorporation with common detection devices. This appears to be a niche capability in the sense that a training exercise can be implemented without having any real CBRN in the atmosphere and still give realistic readings to both the incident commander and team in the field. Currently there are a number of products that simply detect or identify radiation but are not fielded due to cost. However, for training purposes, there are few locations that can use live sources that will trigger the device to set off different alarms. This sensor is remotely connected to a desktop that tracks motion. When the user moves into an area that has been marked contaminated on the desktop it will set off the alarm for the team. Additionally, the person sitting at the desktop can play as the white cell operator and throw different events or even change wind patterns to reflect a change in the scenario.

With these types of capabilities, it could be of great benefit to users of the Polaris system to see how different a tool it is and yet no matter the location, training could occur. Part of the challenge with training in the radiological realm is the fact that most locations will not allow training to be conducted in their territory, let alone in a foreign country. Polaris is a unique sensor and like most devices, the operators improve with more practice. Enabling the operator to conduct more realistic training with a radiation simulator such as the systems offered by Argon Electronics, would raise the bar not only on individual training but team training. Not to mention building partnerships with allied nations and conducting CWMD exercises with them utilizing this type of equipment would alleviate the operational challenge of using live sources and yet still promote advanced training.

Argon Electronics is not the only company looking at improving training for CBRN responders, Alion Science and Technology has developed their own CBRN training tool that can be utilized on any Android phone called Virtual Radiation Training through Ubiety System (VIRTUS). It is relatively new software that uploads on mobile devices an image of the radiation detection device that a typical team would take into the field. Once the image of the radiation detection device is on the phone, it acts as if it were the real thing to include delays to turn and off a radiation detector. One of the significant advantage is that any radiation detection device software package can be uploaded to a phone for training purposes. Whereas the competitor's equipment was an actual device in-hand that was a direct mockup of the original, the Alion device would always be a mobile device with a pancake probe, personal radiation detector, or identifinder image on a screen. The user just needs the VIRTUS software downloaded and radiation source emulators the size of a quarter as opposed to bringing a suitcase of different mockup equipment ("VIRTUS Summary," n.d.). A potential deciding factor for the military is whether they want to invest in new technology that requires a suite of gear or something light and portable that can be conveniently loaded on a phone such as the product Alion developed. During I/ITSEC 2015, Forging the Future of the Marine Corps Training, Commandant of the Marine Corps, General Neller specifically stated new training devices needed to be light and deployable (Neller, 2015).

Of note, Alion Science and Technology's new device does not detect all CBRN, strictly radiation detection, unlike the Argon Electronics product that was on display at I/ITSEC 2015. However they do have other devices that were not on display such as Force-on-Force Evaluation and Analysis of Key Performance Parameters (FREAK) which received a substantial contract from DTRA in 2014 (BioPrepWatch Reports, 2014). FREAK advocates a live virtual constructive capability to enhance training, realism, and interaction between team (Jacobs, 2015).

III. METHODOLOGY

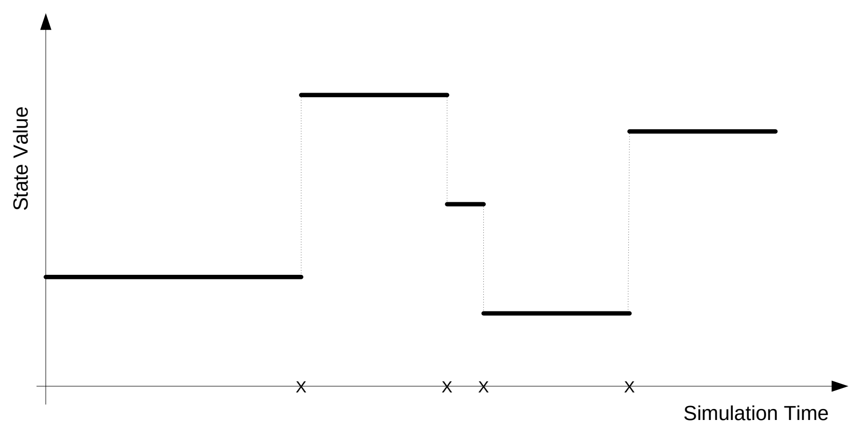
A. DISCRETE EVENT SIMULATION

1. Discrete Event Simulation

Discrete Event Simulation (DES) is the basis for the model developed for this thesis. This thesis gives an overview of DES modeling. A DES has three elements: the states, the events, and the schedule between the two (Buss, 2011, p. 5). The collection of these elements forms the foundation of the DES and can break down even the most complicated problem. For simplicity, this thesis will discuss the basics of a DES and why it was chosen to model the Polaris.

One part of a DES model is the state variable. The state variable is an object that can change value once or multiple times during a simulation (Buss, 2011, p. 5). For example, an employee driving to work can be categorized into a number of different states while in route. He could be at a stop light, on the highway, or in parking lot and each would change the associated values with that given entity. The transitions between these states are piecewise constant, and therefore have a natural leap from one state to as depicted in Figure 6.

Figure 6. DES state trajectory



The values of the state variable change instantly from one state to another during the simulation, thus piecewise. As such, a modeler always knows the state of an entity at any given time during the simulation. Source: Buss (2011, p. 5).

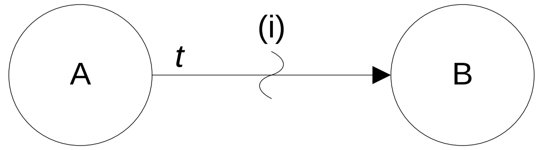
There are challenges with describing state variables, as some occurrences do not happen instantaneously. However, with enough effort added to the DES, these state values can be modeled (Buss, 2011, p. 2). By adding "state transition" or multiple state transitions into the DES, the model can better represent reality (Buss, 2011, p. 5). "The state transitions" are the events and dictate what factor or multiple factors are necessary to identify an entity in a certain state (Buss, 2011, p. 5). The events correspond to all possible states that the entity can change into throughout the simulation and thus assist in scoping a scenario.

In order to determine how the entities in the DES transition from one state to another, there must be a system in place that schedules these events to occur. In a time step model, five seconds could be another point to record state information. However, for a DES, it is the event that causes a "next event" (Buss, 2011, p. 6). Some events cause follow-on events and step forward through the simulation in this fashion. In simulation time, the events may occur in unequal time increments but logical steps (Buss, 2011, p. 6). Continuing the analogy of the employee driving to work, the employee can be seen in multiple logical states, "at home," "in transit," or "at work." Each prior event schedules the next event and thus the employee in transit would have a pre-calculated time of arrival at work once he enters the "in transit" state. However, a time of arrival may not always be the same as traffic may cause disruption in the arrival time. A DES can still account for this by adding another state to the list of states, one that would be called "in traffic," in which the employee was "in transit" but his speed dropped below 10 miles per hour for longer than 90 seconds. The driver's state may continue "in traffic" or switch to "at work" depending on the distance traveled. This description can more easily be visualized by an event graph.

2. Event Graph

Any DES can be represented by an event graph, and this is the preferred method of building a DES before any coding occurs. Whether the DES consists of two events or multiple events, to build an event graph there must be a relationship between the two events that indicate one leading to another as seen in Figure 7.

Figure 7. Basic event graph



This event graph depicts Event A scheduling Event B with a delay of time t if condition (i) is met. Source: Buss (2011, p. 20).

Although Figure 7 is very basic there is much that can be taken away from a simple event graph such as which event precedes another as well as what conditions must be met in order to schedule the next event. This is especially helpful for building a DES around a radiation detection system since part of the focus relies upon whether the radiation source will be detected. Relative to this thesis in Figure 7, (i) might be the condition that determines whether a radiation source is strong enough to be detected and if so, *t* would be the detection time associated with the run of the simulation. The DES for this thesis is more complicated than Figure 7; however Figure 7 simplifies the concept of a DES (Buss, 2011, p. 20).

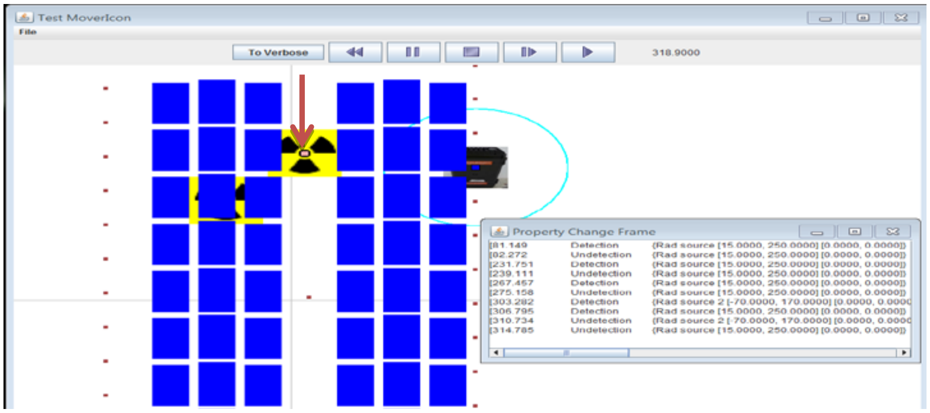
3. Polaris DES

In this thesis a Discrete Event Simulation (DES) model is built of the Polaris sensor moving about a set space while detecting radiation along a given path. The simulation is run multiple times while changing different parameters with the intent of capturing what factors incorporated in the DES are significant with regard to the time to detect all radiation sources. After detection times are recovered and analyzed a determination is made as to whether the system built captures the essence of the Polaris sensor. As mentioned previously, models are only an approximation of reality, and this DES is the first attempt to close the gap between the deterministic model and reality.

The goal of building a DES using Simkit in Java is to emulate as closely as possible the detection characteristics of the Polaris 2.1. Having identical replication is less important than including parameters that can later be adjusted by testers and developers of Polaris as needed. The first step requires creating an object to be detected, in this case the radioactive material source, represented by a small pink square. In Figure

8, the radiation source can be seen in a fixed location and when moused over can reveal the identity of the source such as its size and activity level.

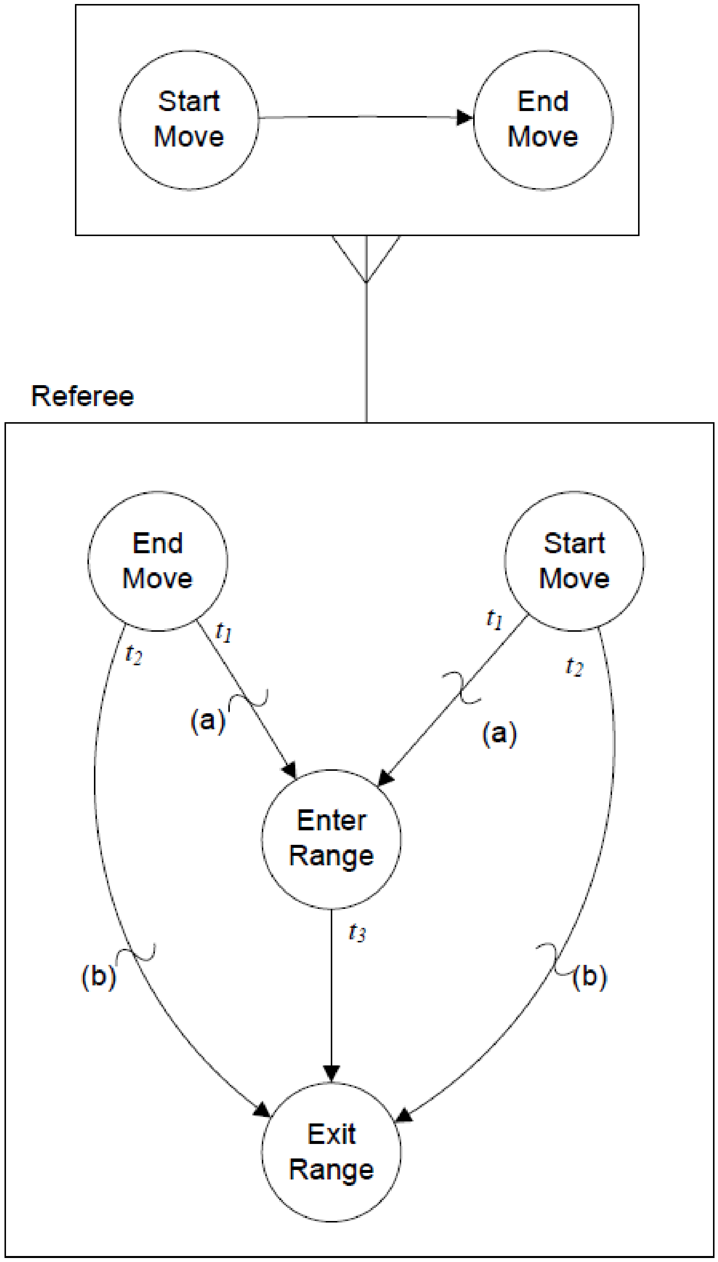
Figure 8. Simkit radiation detection scenario



In this example of the DES the Polaris is the dark icon with a cyan detection ring and the two yellow radiation symbols surround the sources indicated by a pink square. The pink arrow is to emphasize the detection of the radiation source only occurs when the pink square intersects the cyan ring of the Polaris Sensor. One radiation source is in the open and the other inside a container. Source: Screen capture from Simkit.

A class called "basic linear mover" creates additional characteristics needed for the radiation source to be detected so in the instance that the radiation source was moving in a vehicle, the basic linear mover class would handle this action (Buss & Sanchez, 2005). For this scenario the radiation source is stationary and therefore the speed given is zero with the same location of the radiation source. In addition to this class, an additional class called "referee" will determine when the Polaris enters the range of a sensor as seen in Figure 9 (Buss & Sanchez, 2005).

Figure 9. Referee event graph



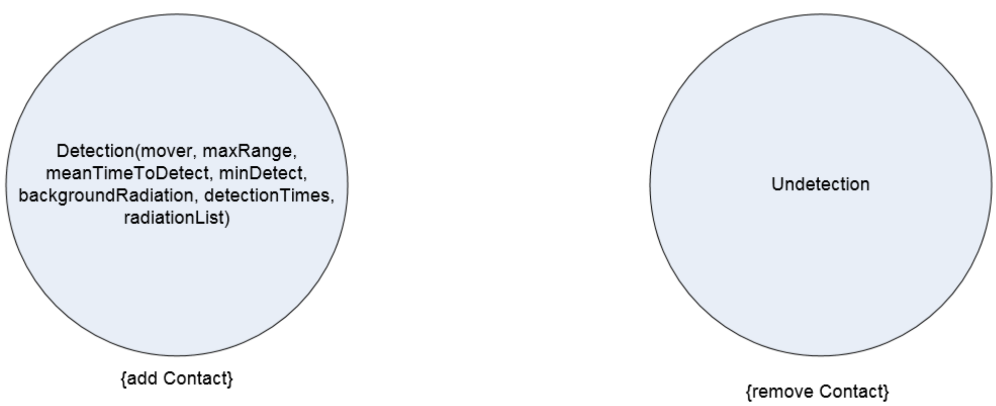
The referee listens to the start and stops of the mover and determines whether or not the Polaris has entered or exited the range of the radiation source. The (a) and (b) annotate a Boolean for entering and exiting range, and for this DES that Boolean was either greater or less than a set distance. Source: Buss & Sanchez (2005, p. 997).

The Polaris sweeps across the built scenario covering all open areas and indicates via a property change frame when detections occur. The Polaris, represented by the

Polaris image in Figure 8 has a circular ring, Polaris sensor, that measures from its center a visible line for the modeler and generates a normal distribution when close enough to the radiation source for probability of detection. Similar to the radiation source, the Polaris also possesses a basic linear mover class which identifies the Polaris unit ID, speed, position, next position, and minimum radiation detection level. The last parameter will allow future modelers the ability to change detection levels to match the Polaris as updates and improvements occur to the system.

In accord with the basic linear mover is the Polaris “constant rate sensor” class as seen in Figure 10 (Buss & Sanchez, 2005). This is similar to the constant rate sensor class with modifications that include time on station as well as a Boolean as to whether a radiation source was detected. The purpose of the Polaris constant rate sensor is to account for all detected radiation sources as well as provide the mediator with the parameters necessary to calculate detection (Buss & Sanchez, 2005, p. 996). The minimum detection level that was originally implemented as a check to indicate whether a source can be detected by the system not necessarily the size of the ring around the Polaris was removed but will be explained later in the future work section.

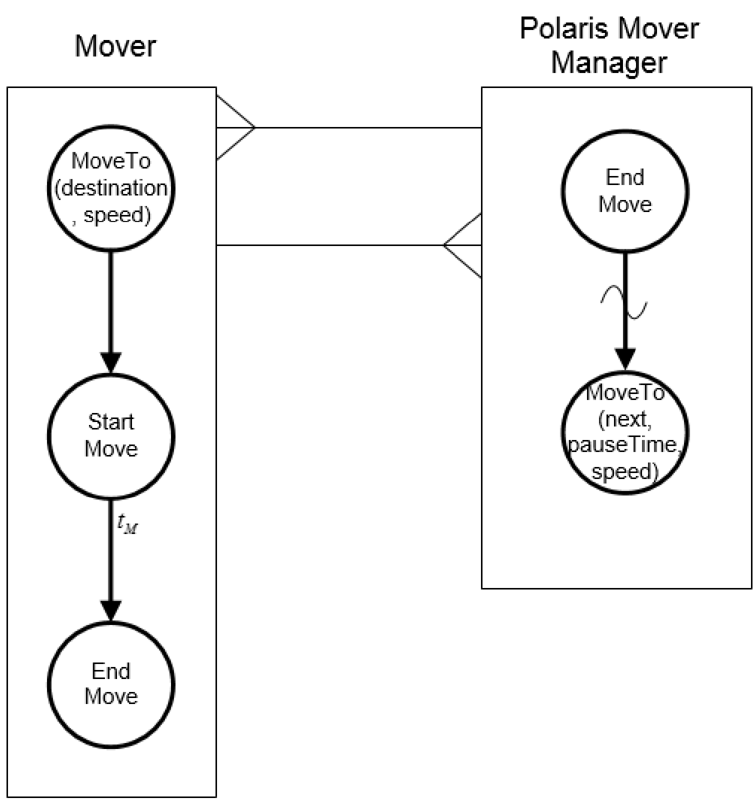
Figure 10. Polaris constant rate sensor event graph



The Polaris Constant Rate Sensor is an extension of the Basic Sensor, taking into account the Polaris Mover, mean time to detect, minimum detection level, background radiation level, an array of detection times and an array of radiation sources. Source: Polaris Constant Rate Sensor Source Code.

To indicate an event occurrence the referee is added to the mover sensors. A pop-up window called a "property change frame" shows the simulation time and location (Buss & Sanchez, 2005). As the simulation runs to completion, the modeler can see the sensor icon moving across the scenario. What the modeler does not see is the mover manager as depicted in Figure 11 or the radiation source levels when placed in different locations. Using the mouse, the modeler can select different icons on the screen to get an additional pop-up window that displays information specific to that entity. There are numerous obstacles the Polaris must navigate around to locate the radiation source and in this simulation the Polaris cannot enter those areas.

Figure 11. Polaris mover & Polaris mover manager event graph



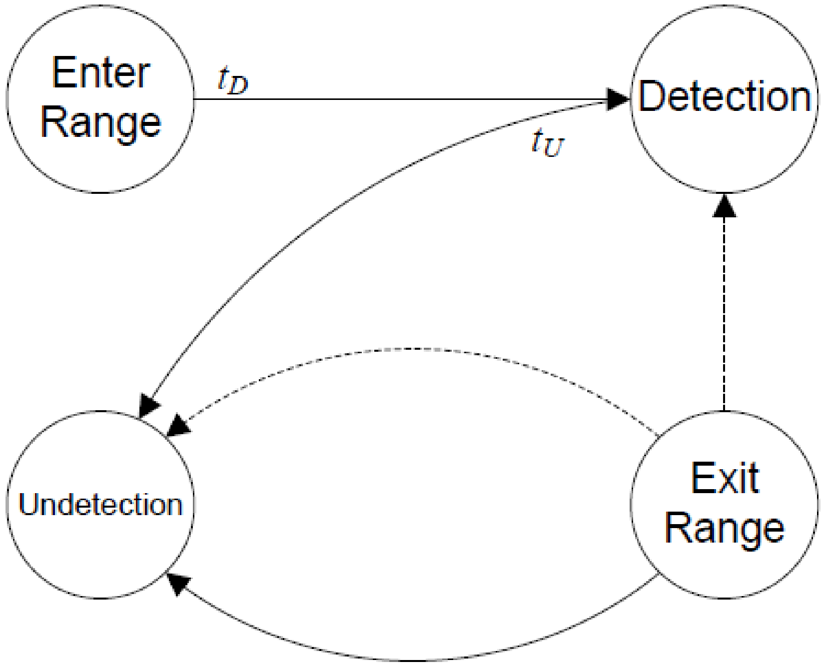
The Polaris mover and Polaris mover manager listen to one another to know when an event has occurred. The Polaris Mover Manager will schedule a movement to the next destination and add a pause at that point if that location is one of the original set waypoints. Since additional waypoints are added because of the obstacles in the path, the mover manager must differentiate which waypoints get a pause and which do not. Source: Buss (2005).

The purpose is to represent the cargo containers and the Polaris must navigate using the basic linear mover class around each obstacle. A radiation source inside an obstacle degrades the signature by a percentage. This is important for the level of detail in the model. There are certain realities in radiation detection that must be incorporated in order to model the scenario.

The display, often called a Sandbox Frame, displays the obstacles in the scenario as well as the radiation sources and radiation detectors but it does not show the path, only the waypoints. Polaris is a relatively stationary device when compared to the more common handheld radiation detection devices. Although transportable, it requires some time to displace and setup. Capturing data on the move can be done with a degraded effect and the scenario requires the radiation detector to move. The simulation leaves the Polaris running throughout the scenario with a constant capability of detection whether in motion or stationary. As mentioned previously, the longer Polaris stays in a single position the more it can capture, and the greater the chance of radiation detection.

In the model, the collected data are passed to a mediator class that is able to compare the collected data from the sensor with the Polaris' detection capabilities. The mediator knows the source strength whereas the sensor only has detected source strength. With this data, the mediator adjusts its rate and probability of detection based on all given factors. Figure 12 displays the relationship between detection and range, just because the Polaris is within range, does not mean time to detect will be instantaneous.

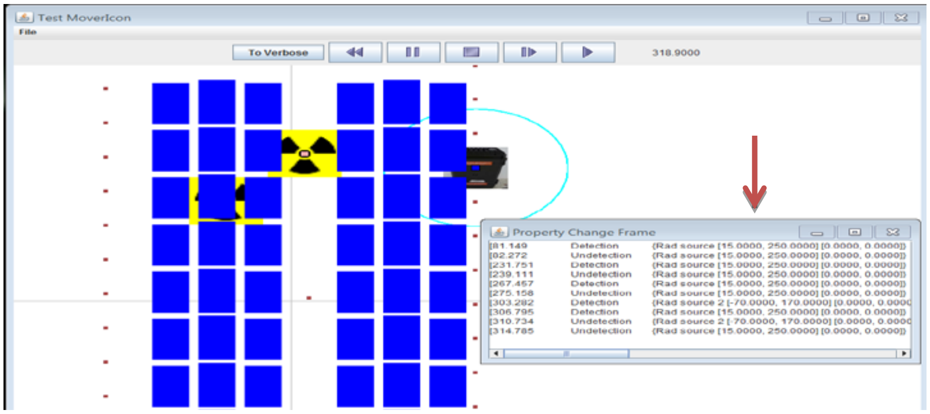
Figure 12. Mediator event graph



The mediator event graph displays calculation time between entering the Polaris range and actual detection of the radiation source. The Polaris DES time for undetection (tU) is always zero whereas the time for detection (tD) is dependent on many factors incorporated into this model such as radiation strength and background radiation. The Source: Buss & Sanchez (2005, p. 998).

The mediator is unique in that it has all data on sources as well as sensor information. With regard to sensor information and sensor collection data, a linear correlation is made for source strength, distance, and time on station. A correlation serves two purposes: the first to mask actual Polaris capabilities and weaknesses and second to give the modeler an avenue to input representative data, whether it is logarithmic, exponential, or otherwise. This gives researchers the ability to use this DES for any radiation detection equipment given they utilize the most accurate representation of the system. This is more fitting to Polaris given that the Polaris continues to make improvements not just in GPS and WIFI capabilities but in capture rates for different radiation levels. Since the sensor in the DES captures graphical data from Figure 13, it can be "mediated" by the mediator.

Figure 13. Property change frame in Simkit



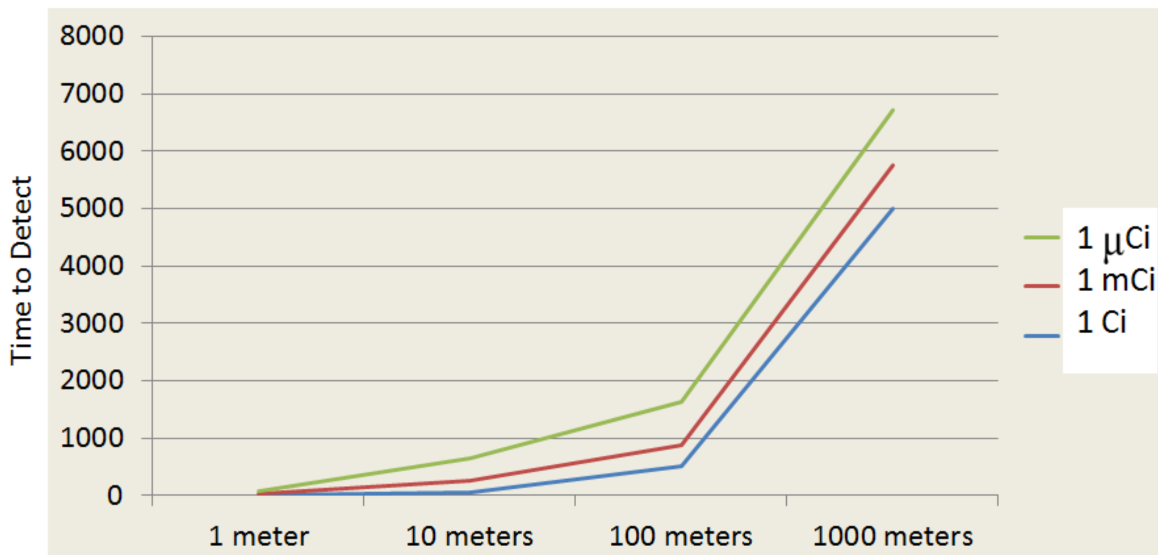
The pink arrow points at the property change frame. In this example every time the Polaris sensor intersects a radiation source, it is logged in the property change frame. This differs from DES used for analysis because only two detection times were captured. Source: Screen capture from Simkit.

Using other tables to represent the sensor gives the DES flexibility and accuracy. In addition it allows for competitor detection devices such as the Germanium Gamma Ray Imager (GeGI3) to be compared side by side. Given the same protocols and implementation the source data and graph can determine which is faster and more effective.

Since the purpose of this thesis is not to endorse or release actual data from any company, all data used remains offset, but realistic of correct technology in the gamma ray imaging realm. The purpose is to identify the factors and/or multiple factors of significance in order to identify better ways of implementing this relatively new device. Implementation is not just how to use, but how to coordinate response and multiple Polaris systems for response operations. Further research would include other radiation detection devices that have been mentioned to complement the Polaris. Smaller and more portable handheld devices that do not have the same detection ranges are often easier to operate, easier to train on, and cost significantly less. However, standoff detection is not nearly the same between the competing systems. Ideally a mix of both systems would be employed to minimize search time. Identifying which combination works best between the smaller systems and Polaris is described in the last chapter.

Probabilities and randomness were included in the model to give realism to the system since the Polaris also carried these traits. As challenging as a real world scenario is to emulate, capturing how radiation works in a simulation is that much more difficult. Simkit and Java offer a variety of methods to incorporate randomness into the program. For this thesis, a random number generator between zero and one is utilized to account for randomness that occurs in real scenarios. The Polaris can be shifted a few feet one direction and detect a radiation source that it did not before, even while keeping distance the same (M. Black, personal communication, September 22, 2015). Therefore a deterministic model such as in Figure 14 may not be the best fit for the Polaris, given the complexities and variations of real world scenarios but at the same time should not be abandoned altogether.

Figure 14. Fictitious sample of Polaris deterministic model with heavy shielding



Adapted from DTRA’s deterministic model is a fictitious representation of the Polaris 2.1 detecting a heavy shielded radiation source.

There are numerous dimensions and densities that can disrupt or reduce the strength of a signal and as such it is imperative that the DES utilize a stochastic model. “Cookie cutter” detection is when a sensor detects an entity immediately and automatically when inside the nominal detection range (Buss & Sanchez, 2005). This makes the “cookie cutter” detection not realistic to imitate the Polaris, so a stochastic model is used instead.

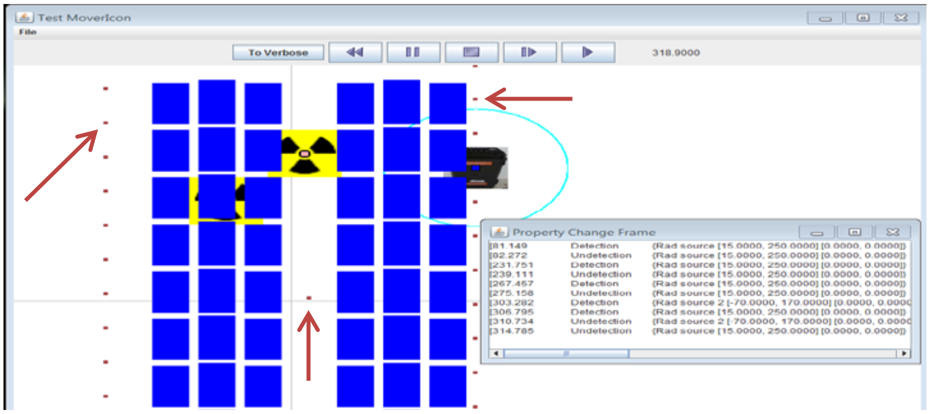
A random variate generates a random number from a given probability distribution and to model variability for the detection of the radiation source once inside the Polaris’ detection range. In the Test Barrier class, a for loop runs the simulation while writing data to a comma separated values (CSV) file. Each run of the simulation will have a new random number in place that takes two parameters for a normal distribution, the mean time to detect and the variance. Since the purpose of the DES is not to dismiss the accuracy of the deterministic model, the first parameter, the mean, was zero whereas the “jitter effect” came from the variance introduced from the random variate generator (Buss, 2016). By doing this the model keeps the accuracy of the deterministic and adds a flavor of reality.

This small change is what makes the DES so important and different from current research. When the Polaris moves from one waypoint to another and the ring of detection encircles a radiation source, if the radiation source is strong enough to be detected, then the detection will be made with a delay based on the variation of that pass.

The discrete event simulation (DES) will detect the radiation source whether the sensor is in motion or stationary at the same rate. The DES does not assume that a system is turning on and off between waypoints in the DES. On the contrary, it detects while in motion from waypoint to waypoint. Additionally it is not advisable to turn the Polaris on and off between measuring points even if battery life is the main concern. The measurement time in the DES is strictly for measurement, and does not include any additional setup or shut down of the Polaris.

For this simulation, the waypoints are the designated stopping points for the Polaris on its path to its final destination as seen in Figure 15.

Figure 15. Waypoints from scenario created

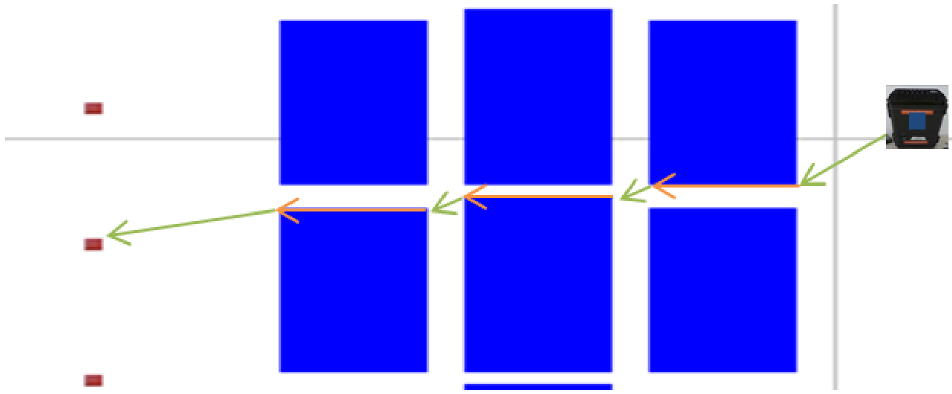


There are numerous waypoints as highlighted by the red arrows, each of which will be a stopping point for the Polaris. Source: Screen capture from Simkit.

The red waypoints are also the original waypoints given for the scenario, however since the Polaris cannot go directly to each waypoint without navigating around objects in the path, additional waypoints are added and vary depending on the number of original waypoints and obstacles in the way. To avoid a cluttered image of waypoints, those ad hoc waypoints are not depicted in the visual representation, however a printout of the waypoints will report all ad hoc waypoints. There is an additional importance to the waypoints indicated with a red dot and that is what will also represent a stopping or pause-point for the Polaris. The Polaris will pause for a set amount of time at each red dot, an originally established waypoint, and this is to replicate what an operator would do when utilizing this equipment while on a vessel or in any given scenario. The default pause time is set to 10 simulation seconds; however, it can be tailored to the user's specification on the test page.

In order for the Polaris mover to navigate to the different waypoints with obstacles in the way, an obstacle avoidance algorithm was created. If there is another waypoint on the path of the Polaris mover, then a Boolean is checked to see if it will intersect the barrier. If there is an intersection, then the algorithm computes the shortest route around the barrier and adds the first edge as the next destination. In Figure 16, the Polaris mover will navigate horizontally to the different red waypoints, and on the fly, add the new waypoints to navigate around the obstacles.

Figure 16. Barrier manager



The Polaris mover has a set path to follow, however the blue containers are obstacles the Polaris must navigate around to get to its next waypoint. In order to do so, a barrier manager class is added to determine if an intersection will occur, and if so then it needs to determine the closest shortest distance around that obstacle by using determining the corners of the obstacle. Once at the next corner, another attempt is made to see if a direct path is possible, if not then another waypoint is generated on the edge of the obstacle. Source: Buss (2011).

B. RADIATION SOURCE

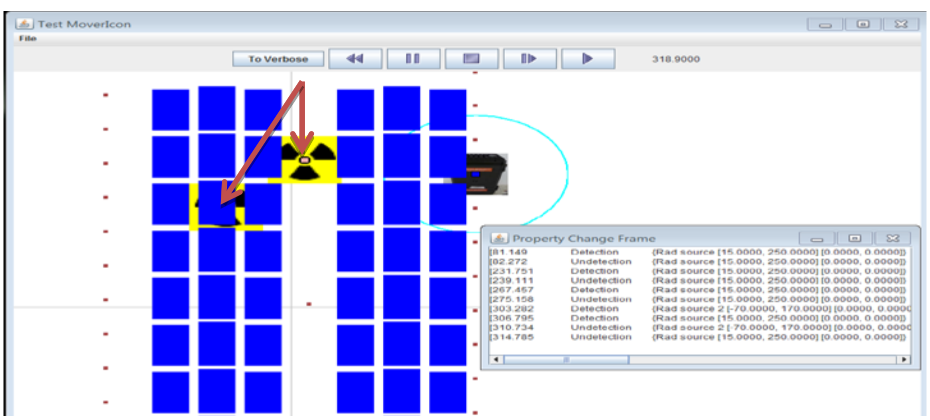
To utilize the DES, Cesium 137 is the sole radiation source modeled. The source, depicted by a pink square and a black and yellow radiation symbol in Figure 17, remains stationary through the simulation. Cesium 137 is typically found as a relatively strong gamma radiation source and is fairly common in the medical industry. With a half-life of 37 years, it is ideal for its longevity whether medical or industrial use. For this reason, Cesium 137 was chosen to be modeled first; however modelers can adjust sources types, strengths, and characteristics into the scenario. The Polaris, being multifaceted, matches isotopes via spectrograph and signature kilo electron volts (keV). This makes it significantly easier for operators in the field to report back to higher headquarters or reach-back experts exactly the source detected.

C. CONTROLS AND FACTORS

The analysis focused on the following set number of factors and controls for the DES a few of which are highlighted in Figure 17:

- Polaris start point
- Polaris end point
- Polaris original waypoints
- Polaris ad hoc waypoints
- Number of obstacles
- Obstacle size
- Obstacle locations
- Number of Polaris detectors
- Detection range of Polaris

Figure 17. Hidden radiation source



The pink arrows point to two radiation sources, one of which is in the open and the other inside a container. Source: Screen capture from Simkit

Looking at Figure 17, one of the radiation sources is inside the object while the other is outside and for this DES only the radiation source inside will get reduced radiation strength due to shielding when in reality both would have some level of reduction based on the shielding between the source and the Polaris.

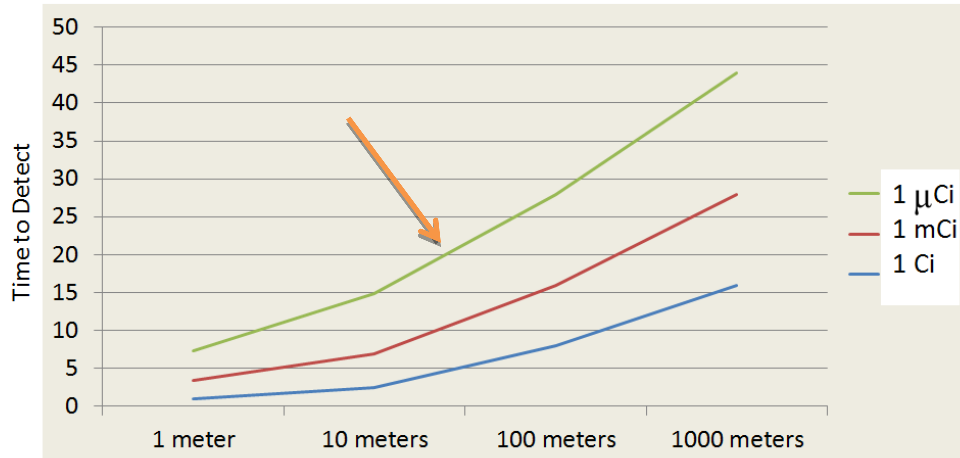
Now that the DES model is built, it needs to incorporate more than just a simple random variate when it enters into the range of the Polaris. Although important, the random variate generated would not take into account the more important factors that are the focus of this analysis such as source strength and shielding. For shielding, a flat rate removal of source strength was utilized not uncommon to linear attenuation but in a much simpler manner. A container ship carries hundreds of containers with a variety of substances that vary in thickness and density, and these have an impact on the time of detection. Implementing these characteristics in the model is potential future work.

There is a formula provided by DTRA used for the DES and enacted when the Polaris sensor is within range of a radiation source. The formula does not replicate the deterministic model entirely, but does align it more closely. The factors taken into account to determine detection time are the background counts per minute, radiation source activity level, distance between source and Polaris, spectral detection, density & thickness radiation source counts per minute at 1 meter, and radiation source count rate in energy region of interest. Of those listed, several are also used as control factors in the DES that could be manipulated in future developments.

- Distance between source and Polaris
- Density & Thickness radiation source counts per minute at 1 meter
- Radiation Source Count Rate in Energy region of interest

DTRA's deterministic formula has a number of differences from the DES model built in Java. The distance used in the DES is fixed at a radius of 100 feet due to the fact that an event is triggered when the Polaris is within range of the source. In the DES, the Polaris will move past the radiation source and at a distance less than 100 feet, however there is no change to the time of detection. The reason being that an event is triggered when entering and exiting the detection range, and while inside that range, there are no continuous checks for distance to take into account moving toward or away from the radiation source. The deterministic model in Figure 18 does show the continuous nature of detection unlike the DES, which falls short in capturing this change. This is a current limitation of the DES model; however future work would do well to manipulate the formula or event list to include a method for incorporating the change in distance to the time of detection.

Figure 18. Continuity of Polaris deterministic model



The continuous line of each measurement from DTRA's deterministic model of the Polaris 2.1 indicates there is a point at which there will always be a detection while in range.

Another significant difference between the DES and the deterministic model is that if the Polaris remains on site for an extended period of time, it will expand its abilities in detection range as well as minimum detection levels. The current DES does not support this capability; this would be another important change to make in order to further align the DES with the deterministic model.

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IV. ANALYSIS

A. JMP

JMP is a tool that can be used to find significance in factors inputted into a data spread sheet or model for this case. JMP was chosen because of its relative ease of use and the number of different runs used during the simulation. There are multiple simulations, each with a fixed set of factors to input, multiple detections per run, and each run changes the variables in the model. This quickly raises the amount of data outputted and captured that must be filtered in order to decipher what factors from the DES created are significant. Not only does JMP do single comparisons but also can do full factorial computations as well bivariate and multivariate computations. The results of calculating the results is what allows us to decide whether or not the DES created did in fact capture the most important factors of the Polaris.

In addition to the significant factors, JMP also provides a tool for testing the effectiveness and accuracy of the DES. Whether a single run of the simulation is used for comparison or multiple runs of the simulation, the amount of code used to create the DES makes it challenging to ensure what has been created is what was intended. Analyzing the output using JMP has helped identify undiscovered discrepancies within the code. JMP does not check if the code is working, but the analysis of the data inputted into the JMP systems allows the user/modeler to evaluate whether the results make sense. JMP does not point out bugs in code the way NetBeans does, however it aids in determining whether the deterministic formula, random variate, shielding effects and radiation source strength are doing what they should when compared to the strictly deterministic formula. Code writing introduces many chances for minor errors that may not be caught immediately and a minor error in a single simulation may have a butterfly effect with multiple simulation runs. This is where JMP assists the modeler to filter through the hundreds of lines of code to sift out what could make these kinds of ripples in the data.

B. DATA ANALYSIS

The initial settings for the factors were set and altered using a Nearly Orthogonal Latin Hypercube (NOLH) design (Sanchez, 2011). The NOLH allows for this DES to be run with design points set to maximize the experiment space explored. With this design, instead of doing permutations through each set of factors, the NOLH can still identify which factors are significant when the input in yellow in Figure 19 is followed. Each row of the NOLH contained 30 iterations in the DES.

Figure 19. NOLH for Polaris DES factors

low level	**0**	**0**	**0.001**	**0.001**	**0**	**400**	**20**
high level	**1**	**1**	**2**	**2**	**6.3**	**600**	**30**
decimals	**0**	**0**	**5**	**5**	**5**	**5**	**5**
factor name	**Shield1**	**Shield2**	**Rad1**	**Rad2**	**Variance**	**ross Cnts**	**M-Time**
	0	1	1.62519	0.75063	1.575	587.5	25.625
	0	0	1.75013	1.12544	0	462.5	26.25
	0	0	0.12594	0.50075	3.9375	562.5	30
	0	1	0.62569	2	3.54375	425	27.5
	1	1	0.87556	0.25088	1.96875	400	28.125
	1	0	0.75063	1.62519	0.39375	550	28.75
	1	0	2	0.62569	5.5125	487.5	29.375
	1	1	1.50025	1.87506	5.11875	525	26.875
	1	1	1.0005	1.0005	3.15	500	25
	1	0	0.37581	1.25038	4.725	412.5	24.375
	1	1	0.25088	0.87556	6.3	537.5	23.75
	1	1	1.87506	1.50025	2.3625	437.5	20
	1	0	1.37531	0.001	2.75625	575	22.5
	0	0	1.12544	1.75013	4.33125	600	21.875
	0	1	1.25038	0.37581	5.90625	450	21.25
	0	1	0.001	1.37531	0.7875	512.5	20.625
	0	0	0.50075	0.12594	1.18125	475	23.125

The figure above splits into columns the different factors that were inputted into the Polaris DES. The first two columns determine whether the radiation source is inside or outside a container. The other columns have more variation such as radiation activity, variance of the normally distributed random variable, gross counts, and measurement time. Each row in yellow had 30 iterations that were then compiled into JMP for further analysis. Source: Sanchez (2011).

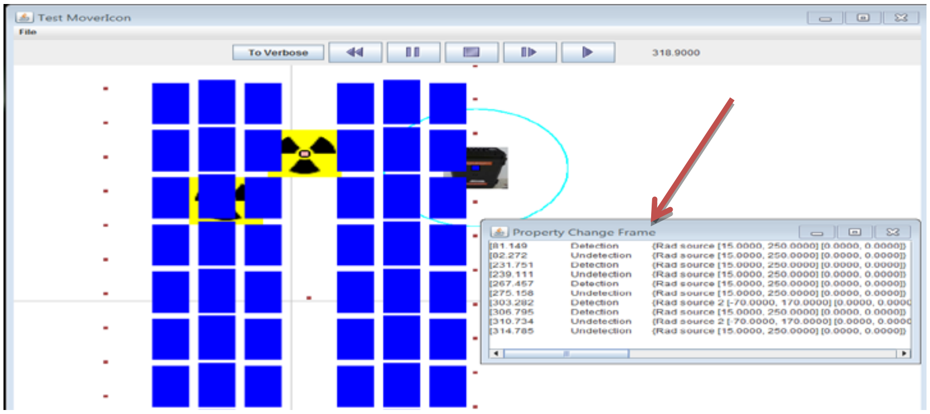
From the design in Figure 19, the factors are continuously toggling. The shield for both radiation source 1 and radiation source 2 do not match even though they both switch between “0” and “1” for each step. The “0” means no shielding was used and the “1” was the opposite. The “low” and “high” levels in Figure 19 were the boundaries set for this DES while the “decimals” pertained to how many numbers after the decimal place were utilized.

To follow the NOLH in Figure 19, the DES read from a comma separated value (CSV) file and inputted the corresponding data into the program. As such, numerous additional checks were added to ensure data read from the CSV file did match the outputted CSV file. The CSV read in had “0” and “1” but the output CSV read “false” and “true” correspondingly. The variance pertained to the variation used random variable added to the deterministic model. Too large of a variance may skew the measure of effectiveness and as such discretion was used on how large of a variation could be added.

The two radiation sources in the DES model toggled between two locations in very near proximity from their origin. One location is inside a barrier and therefore shielded, reducing source strength while the other is not shielded. Since the radiation source is shielded, its strength detected by the Polaris is reduced by 60 percent as a flat rate. The deterministic model DTRA considers light shielding and claims accuracy with its use. However, the purpose is to see how the Polaris would work on a vessel with many possible shields aboard. The toggle is used to capture the shift in radiation strength and it goes between a shielded and unshielded environment.

The measure of effectiveness was the time to detect all radiation sources in the simulation. In Figure 20 the property change frame shows multiple detections of the same source, however for analysis purposes, the single time sought after was the time to detect the second radiation source.

Figure 20. Property change frame



The arrows points to the property change frame which can be prompted to display every detection and undetection. Source: Screen capture from Simkit.

The DES can be modified to annotate each detection of a radiation source for other research purposes if need be. The simulation runs until the Polaris sensor ring exits the second radiation source and then begins the next run of the simulation.

After 30 runs, the program read the next line in the CSV file and began calculations. Each row would have resulted in the same detection time had the DTRA deterministic model been used without an additional random variate. Since the random variate was added, a stochastic effect can be captured with new results after each run. More importantly, JMP allows the modeler to identify which factors have shown significance when other factors are part of the system as depicted in Figure 21. The fifth column in Figure 21 is the t-ratio. The t-ratio is the estimate divided by the standard error (Trochim, 2006). If the absolute value of the t-ratio is greater than 1.96 then it suggests that the value is of statistical significance with 95% confidence (Trochim, 2006). In Figure 21 most of the factors are listed as being significant with an R-square 0.99, which appears to look like a good fit but as pointed out by the red arrow, it is “Biased” or “systematically too high or too low” (Frost, 2013).

Figure 21. JMP screen capture of factors from DES

Parameter Estimates

Term		Estimate	Std Error	t Ratio	Prob>|t|
Intercept	Biased	-359.2684	5.218127	-68.85	<.0001*
Rad1 activity	Biased	-115.951	0.534368	-217.0	<.0001*
Rad1 In Container[FALSE]	Biased	14.250682	0.641246	22.22	<.0001*
Rad2 activity	Biased	70.933521	0.655445	108.22	<.0001*
Rad2 In Container[FALSE]	Biased	-1.81014	0.281076	-6.44	<.0001*
Background radiation level	Biased	27.267852	0.239454	113.87	<.0001*
Variance	Biased	19.061216	0.387331	49.21	<.0001*
(Rad1 activity-0.76173)*Rad1 In Container[FALSE]	Biased	181.7449	2.085563	87.14	<.0001*
(Rad1 activity-0.76173)*(Rad2 activity-0.76635)	Biased	-607.2332	14.98786	-40.51	<.0001*
(Rad1 activity-0.76173)*Rad2 In Container[FALSE]	Biased	492.11465	13.021	37.79	<.0001*
(Rad1 activity-0.76173)*(Background radiation level-20.2963)	Biased	-54.06042	1.552509	-34.82	<.0001*
(Rad1 activity-0.76173)*(Variance-3.1562)	Biased	-303.2744	3.885671	-78.05	<.0001*
Rad1 In Container[FALSE]*(Rad2 activity-0.76635)	Biased	-216.0519	6.897069	-31.33	<.0001*
Rad1 In Container[FALSE]*Rad2 In Container[FALSE]	Biased	-31.76764	1.027788	-30.91	<.0001*
Rad1 In Container[FALSE]*(Background radiation level-20.2963)	Biased	116.31662	1.025127	113.47	<.0001*
Rad1 In Container[FALSE]*(Variance-3.1562)	Biased	214.06417	2.08808	102.52	<.0001*
(Rad2 activity-0.76635)*Rad2 In Container[FALSE]	Biased	-985.9046	8.399139	-117.4	<.0001*
(Rad2 activity-0.76635)*(Background radiation level-20.2963)	Zeroed	0	0	.	.
(Rad2 activity-0.76635)*(Variance-3.1562)	Zeroed	0	0	.	.
Rad2 In Container[FALSE]*(Background radiation level-20.2963)	Zeroed	0	0	.	.
Rad2 In Container[FALSE]*(Variance-3.1562)	Zeroed	0	0	.	.
(Background radiation level-20.2963)*(Variance-3.1562)	Zeroed	0	0	.	.

JMP output from data collected from discrete event simulation model shows the different significance of each variable. Although the numbers highlighted in orange are significant and the R-Square value is extremely high, the estimates should not be trusted. Source: Screen capture from JMP; data pulled from Simkit.

After analyzing the data through JMP using a 2-degree interaction model, there were many significant factors as depicted in Figure 21. 2-degree interaction means all single factors and a multiple of that factor with another were analyzed. Of note, all factors with the exception of shielding go into the DTRA formula to calculate and determine the delay time in the detection of the radiation source.

Radiation activity for radiation source 1 was the most significant factor listed in Figure 21. However, most of the single sources were also listed as significant such as radiation activity for radiation source 2, background radiation, variance, and over a half dozen two-way interactions between them. It appears the model was over fit since each factor was well above the 1.96 threshold. Additionally, the R-square value of 1 was also given from the JMP model, which is another cause for alarm. The R-square value "is a statistical measure of how close the data are to the fitted regression line" and the higher the R-square value the better the "model explains all the variability"; however, a value of one is cause for suspicion (Frost, 2013). As such, another attempt using JMP was utilized to model the results from the DES as seen in Figure 22.

Figure 22. Single factor JMP model

Summary of Fit

RSquare	0.505263
RSquare Adj	0.497332
Root Mean Square Error	71.14636
Mean of Response	137.8624
Observations (or Sum Wgts)	508

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-44.96653	20.45417	-2.20	0.0284*
Rad1 activity	-56.70722	6.41291	-8.84	<.0001*
Rad1 RV	2.9518057	1.402526	2.10	0.0358*
Rad1 In Container[FALSE]	-11.01941	3.397423	-3.24	0.0013*
Rad2 activity	-54.4436	6.398835	-8.51	<.0001*
Rad2 RV	-0.680919	1.570763	-0.43	0.6648
Rad2 In Container[FALSE]	3.5852624	3.266516	1.10	0.2729
Background radiation level	15.712172	0.915391	17.16	<.0001*
Variance	-17.47376	1.869695	-9.35	<.0001*

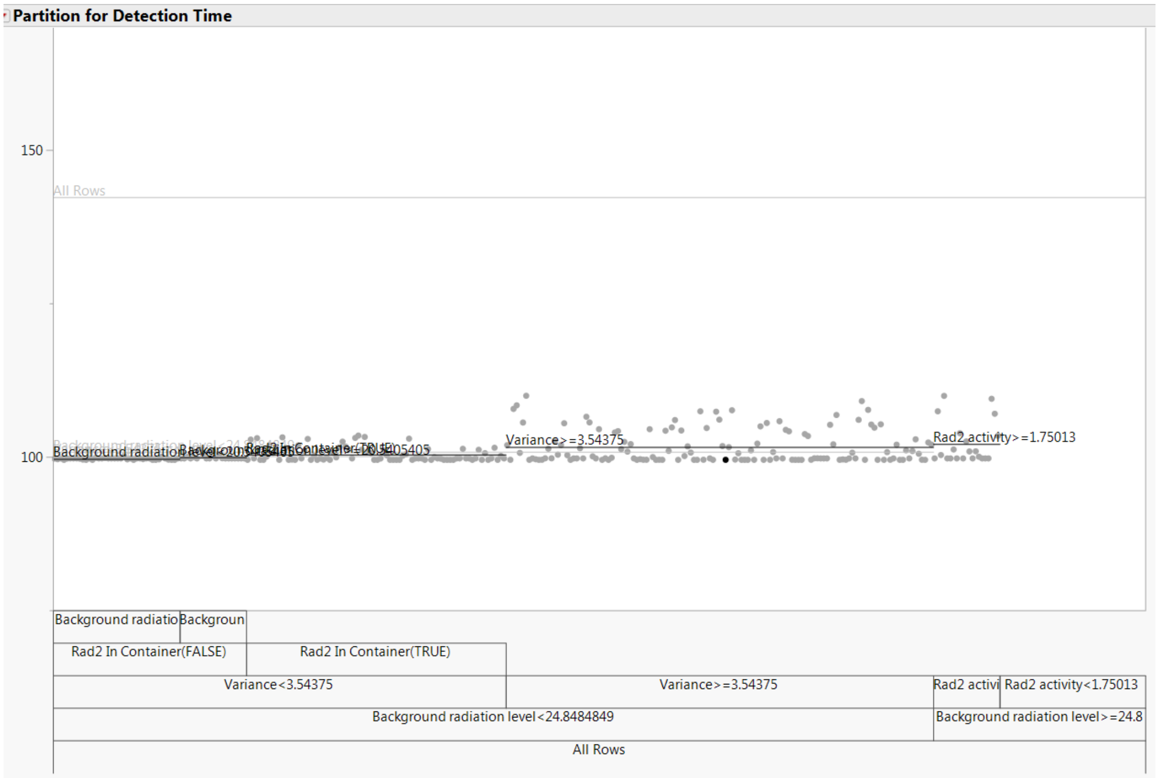
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Rad1 activity	1	1	395796.3	78.1927	<.0001*
Rad1 RV	1	1	22421.2	4.4295	0.0358*
Rad1 In Container	1	1	53250.4	10.5200	0.0013*
Rad2 activity	1	1	366435.1	72.3922	<.0001*
Rad2 RV	1	1	951.2	0.1879	0.6648
Rad2 In Container	1	1	6097.9	1.2047	0.2729
Background radiation level	1	1	1491296.9	294.6177	<.0001*
Variance	1	1	442116.6	87.3437	<.0001*

JMP output from data collected from discrete event simulation model shows the different significance each variable. Although the numbers highlighted in orange and red are significant, the R-Square value is relatively low at 0.505. Source: Screen capture from JMP; data pulled from Simkit.

The JMP model in Figure 22 took into account single factors unlike the JMP model in Figure 21. As a result there were much fewer significant factors and as a result the R-square value dropped to 0.505. It appears the model in Figure 21 is over-fit and the model in Figure 22 is under fit. Another approach was attempted to classify which factors were most significant using a Partition Tree from JMP as seen in Figure 23.

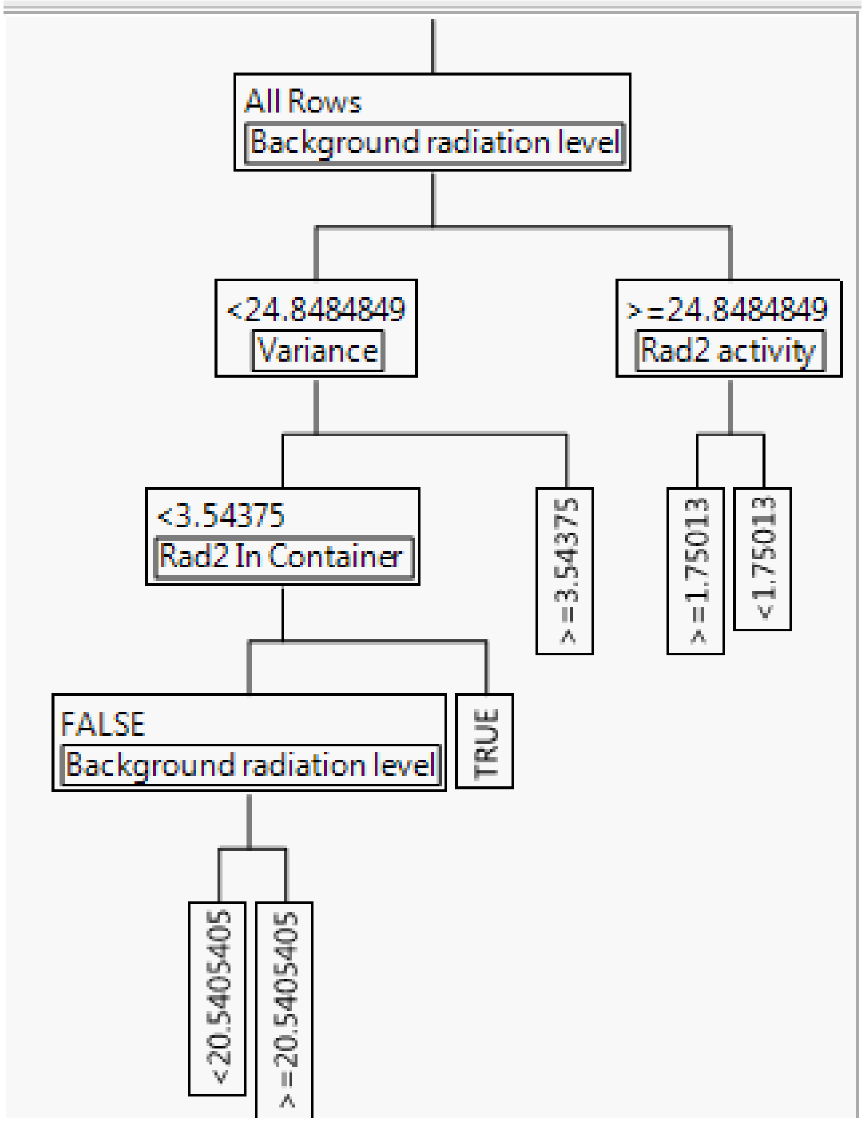
Figure 23. Bottom portion of partition tree of DES captured data



This figure compiles and partitions the detection time into segments that allow the modeler to quickly see which factors or multiple factors were relevant to the measure of effectiveness. The partition tree extends beyond the page along the Y-axis and marks a pocket of detections just above time 400. Source: JMP screen shot.

The partition tree in Figure 23 has the variables listed and partitioned into sections depending on how they influence the time to detect. The tree is split in half at the base by a background radiation level either above or below 24.84. As the modeler navigates through each branch toward the center of the model, it will interact with different variables along the way and eventually land on a data point. Another way of displaying the tree is through a top down approach as seen in Figure 24; however this does not offer the view of the data points.

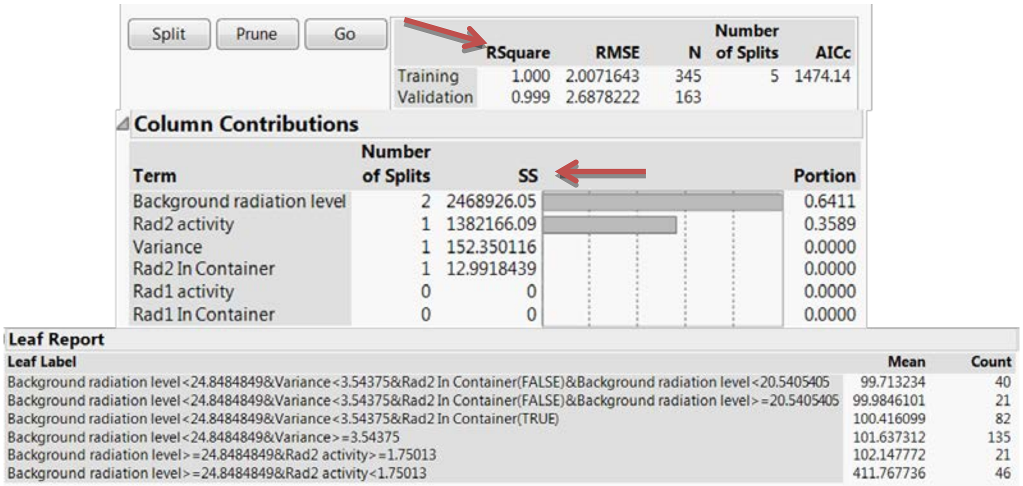
Figure 24. Top down of partition tree



This figure is just another look at the same model of the data from the DES. The Background radiation is the first split followed by variance on the left and radiation activity of source 2 on the right. Source: JMP screen shot.

The partition tree displayed in Figure 23 and Figure 24 do provide ideas of how the factors may interact however it must be followed with more context. The background radiation level is the base for the model and as such carries the most weight in the sum of squares as seen in Figure 25.

Figure 25. Column contributions of partition tree



Split Prune Go

	RSquare	RMSE	N	Number of Splits	AICc
Training	1.000	2.0071643	345	5	1474.14
Validation	0.999	2.6878222	163		

Column Contributions

Term	Number of Splits	SS	Portion
Background radiation level	2	2468926.05	0.6411
Rad2 activity	1	1382166.09	0.3589
Variance	1	152.350116	0.0000
Rad2 In Container	1	12.9918439	0.0000
Rad1 activity	0	0	0.0000
Rad1 In Container	0	0	0.0000

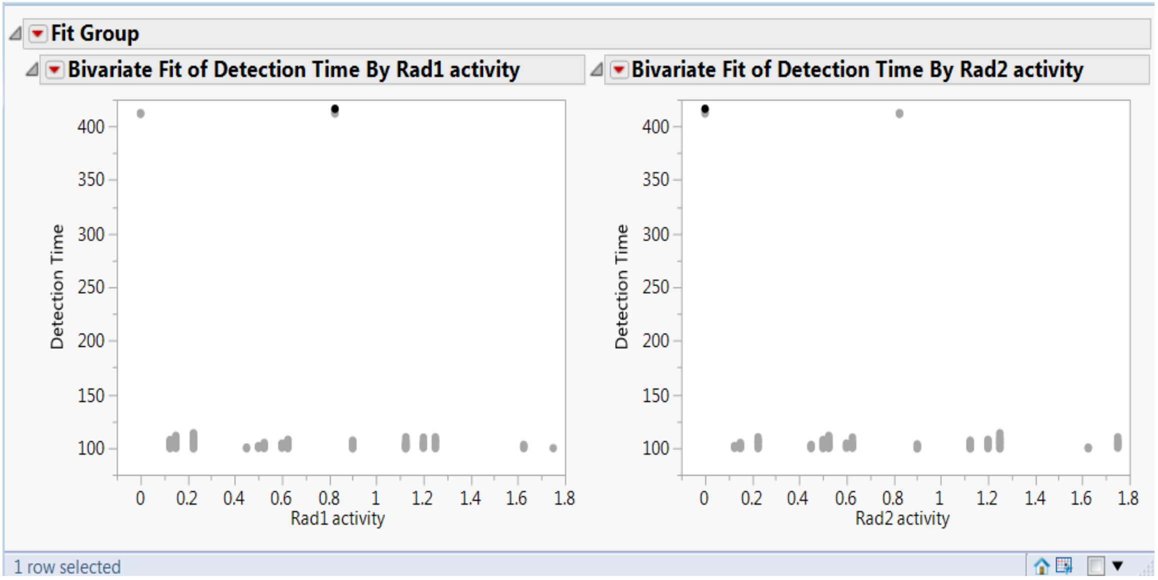
Leaf Report

Leaf Label	Mean	Count
Background radiation level<24.8484849&Variance<3.54375&Rad2 In Container(FALSE)&Background radiation level<20.5405405	99.713234	40
Background radiation level<24.8484849&Variance<3.54375&Rad2 In Container(FALSE)&Background radiation level>=20.5405405	99.9846101	21
Background radiation level<24.8484849&Variance<3.54375&Rad2 In Container(TRUE)	100.416099	82
Background radiation level<24.8484849&Variance>=3.54375	101.637312	135
Background radiation level>=24.8484849&Rad2 activity>=1.75013	102.147772	21
Background radiation level>=24.8484849&Rad2 activity<1.75013	411.767736	46

The R-square value has increased when doing modeling via partition tree instead of using a fit model. The column contribution highlights the summary of squares, marked SS, and states which factors had the higher proportion. Source: JMP Screen Shot.

The modeler can pull from Figure 25 the mean time to detect for a specific path or "leaf" as well as the count associated with it. For this model, the top leaf in the leaf report has the smallest average detection time. In summary, a low background radiation, low variance, and radiation source 2 not inside a container will lead to the lower detection time. However, more significant is what leads to higher radiation detection time. Looking at the last leaf, it sums up that a radiation source activity below 1.75 in conjunction with an elevated background radiation level will result in a higher detection time. In addition R-square for this model is 1.0, giving cause for suspicion once again. Therefore, looking at a bivariate fit of the two radiation sources as seen in Figure 26 aids in explaining why there is such a vast change in the mean.

Figure 26. Bivariate fit of radiation x detection time



The image above has two data points that are highlighted in black. Each of those marks a time when the detection times were remarkably high, nearly four times the mean. As seen above, when the radiation activity level is at 0.001 for either radiation source 1 or radiation source 2, the corresponding detection times were above 400. Source: JMP screen shot; data from Simkit.

In order to conclusively determine how accurately the DES created did replicate the Polaris by accounting for the deterministic model accurately, adding stochasticity, and not compromising the integrity of the model a laboratory experiment will need to be conducted. The DES functioned as expected and was able to retrieve data from the prebuilt NOLH datasheet however the measure of effectiveness did not conclude as anticipated. Looking at the rows from the NOLH and comparing them to the results without using JMP, it does appear to make sense. The lower the radiation activity level coupled with shielding and high background radiation the longer the time to detect. This was the typical result but further studies are required to conclude what additional changes would enhance the Polaris DES.

V. CONCLUSION

A. DISCUSSION

This discrete event simulation (DES) mimicked some of the key aspects of the Polaris 2.1. There were significant challenges with this task, yet the DES is a good first step towards closing the gap between the Polaris and a DES. This DES modeled a mobile sensor that can maneuver from waypoint to waypoint, determine the shortest distance to navigate around obstacles, and can detect radiation at a given distance. The states, events, and the schedule between them all had to be incorporated and focused on a novel radiation detection device (Buss, 2011, p. 5). The deterministic formula for finding the time to detect a radiation source was critical to create the DES. By adding to this formula some representative anomalies that occur in natural settings, the DES was enhanced with realism. Even at a fixed radius, different geometries and attenuation can have effects on the time to detect a radiation source that are difficult to capture in a deterministic model. This DES accounted for those anomalies in a single stochastic model. In addition, with repeatable iterations, the data captured was inputted into JMP for further analysis in order to find what factors weighed most heavily in the DES. The findings were conclusive that the deterministic model provided by DTRA was the single most important factor. However, there were a substantial number of other factors added to the DES that also were determined to be of significance. It is those secondary and combination factors that will lead to answering the question of how to best employ a unit equipped with a Polaris in a given scenario.

This DES is generic enough that any moderate programmer with skills in DES and Java can continue this work in search for the optimal use of this equipment. The ground work has been laid out the possibilities range from scanning ports for weapons of mass destruction to sifting through a junkyard to ensure incidences like Goiânia do not happen again.

B. FUTURE WORK

One major factor is that the Polaris will continue to develop into Polaris 2.2 and eventually Polaris 3.0; meanwhile the DES will remain in the originally created state. Unless adopted as follow-on work by another researcher in the DES and radiation realm, by DTRA, or by one of the national research laboratories, the DES will not progress from emulation to optimization. Just as the Navy and Marine Corps and other services run simulations to determine how to best employ their infantry, artillery, tanks, ships, and radar systems, the same research is needed with this evolving technology. Laboratory experiments are great for learning about the specific system itself, however expanding that purpose and implementing Polaris in an operational and strategic mindset to see how this system can become a force multiplier for the United States and its national security. The DES of the Polaris is merely a first step in that direction to discover its full potential. Additionally, users and subject matter experts may be focused in a microscopic vice macro-level view point and miss the opportunities to address vulnerabilities and gaps. Admittedly, addressing said gaps and vulnerabilities will lead to classifications above this research; however, with the benefit of maximizing the capabilities of the Polaris and minimizing those gaps in radiation detection, the operators are in the best situation to detect hidden radiation sources in the shortest amount of time.

If further research is not desired for the Polaris, tackling the GeGI3 and developing a DES model based on its deterministic model may also be of added benefit. Although DTRA invested in the Polaris, Lawrence Livermore National Laboratory believes in the capabilities of the GeGI3 and as such analysis of the model and simulations as well as live side-by-side experiments maybe cause for DTRA to reevaluate the current contract. If there is no clear or significant added benefit to changing, then maybe there are areas of enhancement where one system can determine based off a DES and experiments, what factors inputted into the system make the most operational impact when fielding these types of radiation detectors. While this thesis answered a single question, many more are raised on how to improve the system.

1. Polaris Discrete Event Simulation Model 0.1

The discrete event simulation (DES) developed in this thesis is an important first step in modeling the Polaris system as it might function in the field. As such there are many placed where it could be enhanced. The DES enhances the deterministic model, by adding in randomness, this makes it a stochastic model. However there are plenty of areas for improvement for users and modelers to build this initial version. A graphical user interface (GUI), can facilitate varying the different factors into parameters that more accurately represent the Polaris past and present versions. The user can do this with the current DES, but it requires a user that is familiar with reading code, whereas a GUI interface would be something any user could understand and manipulate without coding experience. For someone attempting to do further analysis of alternatives work with Polaris before going into experimentation, this may be of great benefit. With all the factors centrally located, the user could modify the scenario with a few button clicks and find the optimal scenario for using the Polaris with more ease that the current version.

Finding a solution to incorporate the distance between the source of radiation and the Polaris, whether inside or outside the detection ring, would be beneficial to the DES. This method would make the detection time more realistic and more in line with the deterministic model. Currently the DES only takes in the distance once the enter range event has occurred and does not factor in the change in range that occurs while inside that detection ring. An improvement would be if the radiation source had rings around it that delineate different levels of source strength. Following the 1/4 rule for radiation, doubling the distance from the radiation source reduces the exposure rate to 1/4 and vice versa (Taylor, 2001, p. 257). Different colors surrounding a radiation source would indicate the multiple strength levels and as such when the Polaris moves through an area it would recalculate detection based on the strength of the source.

The strength of the source in the DES is directly affected by whether or not it resides in a shield; however the DES currently does not taking into account the other shields that are between the Polaris sensor and the radiation source. To model this one could assign each box a random variable of source reduction capability. A light, medium, and heavy shielding would be randomly dispersed throughout the different containers and would add a better method for capturing shielding with regards to the DES created for this thesis. In addition, subcomponents of those shields could be subdivided into another set of random variables of shielding that would take into account an uneven shielding within a single unit. A vehicle inside of a container may be very dense in the engine and have a different shield capacity compared to the bed of a truck.

Another addition to enhance the model is a minimum detection threshold for the sensor inside the DES. A radiation source can be inside the detection ring but if the source is radiating at too weak of an activity level, it will not be detected by the Polaris. This is consistent with real detection scenarios as it would be unrealistic to expect an operator to wait at each designated measuring point for hours. Therefore this characteristic could be added to the DES and further research can determine how long that operational pause at each designated waypoint should be.

A change in the basic scenario altogether may also be of use. A gamma source that can penetrate through multiple layers and densities at a significant distance makes this scenario, when fully developed, relatively challenging for a DES. Changing the DES scenario to a simpler scenario with fewer densities to configure and calculate for maybe a more suitable next step in developing a realistic scenario for the DES. This does not preclude future work from continuing with the barge scenario; however the simpler scenario would further reinforce the formula and methods used. Such scenarios can easily be configured with the current DES.

With a functioning DES, new scenarios can be created taking into account some of the other controls that were fixed for this thesis. For example, the path and waypoints selected for doing an initial sweep as well as a pattern for that sweep can be remodeled and incorporated into the DES. The DES currently runs with an operator conducting an initial sweep of the area of concern without reinvestigating any sources suspected. This technique is taught at DTRA’s Defense Nuclear Weapons School (DNWS). However, they do not utilize the Polaris for these sweeps and may be another area to consider making changes. The DES does pause at the determined waypoints with the intent of future work enhancing the detection capability as the Polaris remains stationary. The reason DNWS does an initial sweep is to avoid the operator from fixating on a particular area that may be the wrong site of the actual radiation source. When the geometries of the scenario make detection more complicated, an initial sweep of the entire area of concern can help determine the true location of the source. However, do the current tactics, techniques, and procedures (TTPs) for radiation detection make sense with the added capabilities of the Polaris? With a large number of container ships with different densities, triangulation may be of more use than just an image. Additionally, the operator may want to do pauses between the waypoints displayed in Figure 20, Chapter IV. This would also support the Polaris while the triangulation capability comes online.

2. Testing

Incorporating previous work at Los Alamos National Laboratory, a DES built in a different system called FLEXSIM, focused on dose and radiation exposure for future planning of nuclear facilities (Tompkins et al., 2004, p. 1). Although the purpose of their simulation in FLEXSIM focused on dose not detection, there is still application to this thesis with regard to calculations for shielding and enhancing this DES. Either combining the two models or incorporating one build into another, the future work for this topic can be greatly enhanced with the model built in FLEXSIM. Taking into account that part of the shortfall of the DES created for this thesis is the simple incorporation of shielding, FLEXSIM or possibly the formula used to calculate the radiation levels may be of added benefit into this DES.

In addition to working with Los Alamos National Laboratory (LANL) to incorporate their successes with FLEXSIM with this thesis, another added benefit would be working with DTRA, LANL, LLNL, DHS, and other key players to increase the capability of the DES but more importantly to find an optimal scenario for the Polaris. Pulling from gap analysis and deciding how to incorporate this system into the realm of radiation detection effectively will have the greatest impact. It may be that further analysis with this equipment determines the Polaris is not the game changer detection DTRA would like it to be however that analysis needs to be conducted to see if that is the case or vice versa. What scenarios does the Polaris have the best fit? Sweeping a ship and searching for radiation source or stationary in an inconspicuous container taking measurements as cargo or people move past. These are the kinds of questions researchers will be able to answer with further analysis. That analysis will inevitably lead to enhanced use of radiation assets, better detection capabilities, and safer borders.

3. Hardening

The Polaris communicates can communicate with multiple devices, such as tablets, laptops or desktop computers to relay information; however this also highlights the potential for hacking and spoofing. Ensuring the information passed from the Polaris to the user's device does not get spoofed information by hackers is a challenge for any electronic system but more so for defense systems looking to thwart terrorist activity. With more terrorist activity taking to the cyber highways in order to deny service or hijack capabilities, it is imperative for the developers of the Polaris to reinforce information assurance measures that exceed the normal DOD electronic device. While this work is beyond the scope of this thesis, it is an important area to explore.

Another relatively cheap attack on the Polaris is a mini-electromagnetic pulse (EMP). A mini EMP would not have the catastrophic effect of nuclear blast, nor would that be the need. Instead, a mini-EMP would be used to allow disrupt service of the Polaris while conducting a survey aboard a vessel or in a room. The mini-EMP or multiple mini-EMPs would not require large target areas but enough to delay and or disrupt the detection of radioactive material by a digital device. Given a direction, this device could be enough to allow more than just an RDD through a port, but something with a more devastating consequence such as IND. Research in this field would focus on strengthening the Polaris from the different soft attacks that Department of Defense equipment has been the target of.

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